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WADC Technical Report 55-185

(Title - UNCLASSIFIED)

RESEARCH WORK ON SUPERSONIC WIND TUNNELS TO
INVESTIGATE THE USE OF PERFORATED WALLS

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G. C. Goldbaum
Defense Research Laboratory
The University of Texas

March 1956

WRIGHT AIR DEVELOPMENT CENTER

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Aeronautical Research Laboratory
Contract AF 33(616)-2673
Project 1363
Task 70121

WRIGHT AIR DEVELOPMENT CENTER
AIR RESEARCH AND DEVELOPMENT COMMAND
UNITED STATES AIR FORCE
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FOREWORD

This report was prepared by the Aeromechanics Division of Defense Research Laboratory, The University of Texas, Austin, Texas. The work reported herein was authorized by Air Force Contract AF 33(616)-2673, Task 70121, Project No. 1363, "Wind Tunnel Studies." The research work accomplished in this program was under the direction of the Aeronautical Research Laboratory, Wright Air Development Center, with Mr. Emil Walk as task scientist.

The technical personnel of the Aeromechanics Division of The Defense Research Laboratory who have been assigned to this project under the supervision of Dr. M. J. Thompson are Mr. G. C. Goldbaum, project engineer, assisted by Messrs. J. M. Cooksey, F. D. Carnahan, and Miss. Reba Beeler.

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This technical report was released for publication by the author in February 1955.

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ABSTRACT

During the initial period of 1 September 1954 through 28 February 1955, the redesign and modification of the two-inch variable Mach number wind tunnel has been accomplished. The Laboratory vacuum system has been expanded and extended to the two-inch tunnel. A flow-measuring circuit was designed and installed to measure the mass flow scavenged through the perforated plates, including the necessary instrumentation and a complete series of flow measuring nozzles. Finally, a series of perforated plates was fabricated to test the effects of variables such as plate porosity, plate length, hole size, and hole aspect ratio. The testing phase was begun, with the first tests including testing of perforated plates of 7.03 and 25.6 percent porosities at nominal Mach numbers of 1.8, 2.8 and 3.8, and with plate angles of attack of 1.0 and 2.3 degrees. The data are presented in the form of logarithmic plots showing the variation of mass flow through the plate (in terms of the velocity ratio, $\frac{v_n}{v_\infty}$) with the pressure drop across the plate (in terms of the pressure ratio, $\frac{\Delta p}{q_\infty}$). Schlieren photographs were made of the flow over a two-dimensional double wedge, and the initial analysis indicates that perforated walls will successfully cancel shock waves at supersonic Mach numbers.

PUBLICATION REVIEW

This report has been reviewed and is approved.

FOR THE COMMANDER:



ALDRO LINGARD, Colonel, USAF
Chief, Aeronautical Research Laboratory
Directorate of Research

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Introduction

This report presents a summary of the work done at the Defense Research Laboratory, The University of Texas, Austin, Texas, during the period 1 September 1954 through 28 February 1955, on "Research Work on Supersonic Wind Tunnels to Investigate the Use of Perforated Walls".

The primary purpose of the research program was to investigate the effectiveness of shock wave cancellation through the use of perforated wind tunnel walls. This need has been emphasized by the contemplated testing of relatively long models in present and proposed wind tunnels. The cancellation of the reflection of the leading-edge or other undesirable shock waves at the wind tunnel walls is necessary in order that realistic free-flight aerodynamic data be simulated. The shock reflection does not exist under free-flight conditions.

It is not practicable to enlarge existing or proposed wind tunnel installations; therefore, it is felt that a method of artificial shock wave cancellation is the immediate answer, the most direct approach being the cancellation of shock waves by mass flow suction through perforated walls. This method has been used quite extensively and successfully in high subsonic, transonic, and low supersonic speed wind tunnels, and it is felt that this method of shock cancellation can be carried over into the higher supersonic regions. The present study is primarily concerned with shock cancellations in the Mach Number range of about 1.5 to 3.5.

Experiments of this general nature have been conducted and reported in Ref. (1). The results indicated that it was possible to define a perforated plate in terms of the relationship:

$$\frac{\Delta p}{q_{\infty}} = k \left(\frac{V}{V_{\infty}} \right)^n$$

where $\frac{\Delta p}{q_{\infty}}$ is the measured static pressure drop across the perforated plate divided by the free stream dynamic pressure. The velocity ratio is determined

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by the mass flow scavenged through the plate, the free stream density and air velocity and the area of the perforated region of the plate, i.e.,

$$\frac{V_n}{V_\infty} = \frac{V_2}{\rho_\infty A V_\infty} .$$

The symbols are defined in the section on nomenclature.

The results of the tests also indicated that the exponent, n , and the viscous loss coefficient, k , could be determined for each plate at each Mach Number, i.e., the slope and intercept of a logarithmic plot of the above expression were functions of the plate porosity, plate dimensions, hole size and shape, hole distribution, and Mach Number. Other effects were also indicated by variables such as the ratio of hole size to plate thickness, the angle of the hole with respect to the plate surface, the shape of the hole inlet, and the surface condition of the plate.

Since results of tests indicated that perforated plates were a practical means of cancelling shock waves at Mach Numbers up to about 1.2, a program was instituted in which the research would be extended to Mach Numbers up to 3.8.

The first phase of the program was designed to cover a period of six months and was to include the investigation of the aerodynamic characteristics of several plates of different perforation configurations, with and without mass flow suction through the plates. Primary variables to be considered were Mach Number and plate porosity.

The first phase of the work at this Laboratory has been completed. This has included redesign and modification of the two-inch variable Mach Number wind tunnel including the complete wind tunnel circuit and related equipment. The modifications included extension of the Laboratory vacuum system to the two-inch circuit. They also included the addition of two

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vacuum pumps to the vacuum system, which was necessary in order to maintain the required pressure drop, and hence mass flow, across the perforated walls. A flow measuring circuit was installed to measure the amount of mass flow scavenged through the perforated plates; the instrumentation was designed and fabricated, including a series of flow measuring nozzles designed according to ASME specifications of Ref. (2). In addition, a series of perforated plates was fabricated to test the effect of plate porosity, hole size, plate length, hole aspect ratio, and plate angle of attack.

The wind tunnel was reworked to accommodate the perforated plates downstream of the nozzle flexible plate. A plenum chamber was installed beneath the perforated plate to provide a relatively large volume at a relatively low pressure, through which the mass flow would be scavenged.

The initial testing has also been completed. Tests were conducted to determine the effect of Mach Number, plate angle of attack and plate porosity on the mass flow characteristics through the plate perforations. These tests were conducted at Mach Numbers of 1.8, 2.8 and 3.8 on plates of 7.03 and 25.6% porosities. The plates were tested at angles of attack of 0, 1.0 and 2.3 degrees.

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Description of Equipment

The tests were conducted in the two-inch by two-inch continuous flow variable Mach Number wind tunnel of the Defense Research Laboratory which can provide Mach Numbers in the continuously variable range of about 1.8 to 3.8. The tunnel normally operates at supply pressures of about 40 psia; however, the operating supply pressure has been increased to about 100 psia for some of the tests on the perforated plates at the high Mach Numbers. The wind tunnel was designed to provide for a perforated wall on the bottom only.

The modified wind tunnel circuit is shown in Fig. 1. Figure 2 is a drawing showing the details of the wind tunnel components, including the plate actuating mechanism and evacuation plenum chamber. Figure 3 is a photograph of the wind tunnel showing the bellows outlet tube and bellows assembly, and Fig. 4 is a photograph of the wind tunnel with the side plate removed showing Plate 2a installed downstream of the nozzle.

The perforated plates tested were two inches wide and six inches long. They were of 7.03 and 25.6 percent porosities and the perforated lengths were about two inches long (one test section height). The hole size was 0.0595 inches in diameter and the plate thickness was 0.063 inches for both plates. The holes were drilled and the top surfaces were smoothed over after drilling. Figures 5 and 6 are photographs of the plates that have been fabricated to date. Plate 2a was in the wind tunnel and hence is not included in Fig. 5. The physical characteristics of the plates are described in detail in Table I.

The mass flow through the perforated plates was determined by a series of flow measuring nozzles. The static pressure across the nozzle was measured by a U-tube filled with silicone oil of specific gravity of about 0.95 and the temperature was measured by a laboratory thermometer inserted a safe distance upstream of the nozzle. Figure 7 is a photograph of the flow measuring nozzles; a 0.75-inch nozzle was also fabricated but

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was in the circuit when the photograph was made, hence is not included in the figure. The flow measuring instrumentation is shown in the foreground of Fig. 1.

The pressure drop across the perforated plate was provided by the laboratory vacuum system whose capacity was increased for this series of tests. A photograph of the pumping system is shown in Fig. 8, and a curve showing the approximate operating characteristics of the system is included in Fig. 9. The pressure drop across the plate was measured by using the average free-stream side wall static pressures measured at several stations along the length of the perforated plate and the static pressure in the evacuation plenum chamber. The pressures were measured by means of a fifty-tube mercury manometer board.

A perforated plate has been designed and built with static pressure taps installed directly in the plate; this will provide a comparison between side-wall static pressures and static pressures directly over the plate.

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Results and Discussion

The work during the initial six-month period of this research program has included primarily the design, modification, fabrication and calibration of the wind tunnel, wind tunnel circuit, instrumentation and related equipment. It was possible, however, to perform some analytical studies and to begin the testing phase.

In order to determine the limitations of using a perforated plate to cancel shock waves at relatively high Mach Numbers, the curves of Figs. 10 and 11 were determined. These data show, for supply pressures of 35 and 50 psia respectively, the maximum values of the pressure ratio, $\frac{\Delta p}{q}$, that are possible for the Mach Number range shown and for the assumed plenum chamber pressures. Included is the value of the absolute upper limit of the pressure ratio, computed assuming that the pressure in the plenum chamber, p_2 , was zero. These data were computed from the relationship:

$$\frac{\Delta p}{q_{\infty}} = \frac{\frac{p_1}{p_0} - \frac{p_2}{p_0}}{\frac{1}{2} \gamma \left(\frac{p_1}{p_0} \right) M^2}$$

Also shown in the figures are curves of the critical pressure drop, $\left(\frac{\Delta p}{q_{\infty}} \right)_{cr}$,

which is defined for the critical pressure ratio across the plate, i.e.,

$$\frac{p_2}{p_1} = 0.528. \text{ Pressure ratios greater than the critical value will not}$$

theoretically produce an increase in mass flow through the plate.

Two perforated plates were tested at Mach Numbers of 1.8, 2.8 and 3.8. The plates were of 7.03 and 25.6 percent porosities. The tests were conducted at plate angles of attack of 0, 1.0 and 2.3 degrees. The maximum angle of 2.3 degrees was limited by the mechanical design.

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The data are presented in Figs. 12 through 15. Additional tests were conducted, but the data are being temporarily withheld from publication until further testing is completed. It appears that an increase in plate angle of attack improves the characteristics of the plates, the larger effect occurring on the plate with the greatest porosity. The data indicate, in general, that a greater pressure-drop ratio is required as the Mach Number is increased for a given mass flow scavenged through the perforated plate.

These tests were conducted with the tunnel empty and were limited in scope; it is felt that additional testing is necessary before definite conclusions can be reached.

A series of Schlieren photographs was made with a ten-degree half-angle two-dimensional wedge in the wind tunnel. These photographs were made at a Mach Number of 1.8 and are shown in Fig. 16 with the Plate 2b installed in the bottom wall of the tunnel.

Figure 16(a) shows the shock wave configuration over the plate with no mass flow being scavenged through the vacuum system. However, it appears that even without artificial pumping (suction) a circulation results from the pressure difference across the leading-edge shock wave. It is believed that the higher pressure downstream of the leading edge shock wave induced a flow through the plate which seems to have partially cancelled the reflection at the perforated wall; however, since the perforated plate extended upstream of the point at which the leading-edge wave hit the wall, the air that flowed into the plenum chamber (aft of the wave) was discharged into the wind tunnel ahead of the leading-edge wave and induced another strong shock wave. This wave can be seen emanating from the bottom wall upstream of the point at which the leading edge shock wave struck the bottom wall. Figure 16(b) shows the effect of maximum suction through the perforated plate, and Fig. 16(c) shows the effect of optimum suction through the plate. Optimum suction is defined as the amount which produces the optimum shock cancellation configuration. Comparison of the photographs, particularly in the region ahead of the point at which the leading edge

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shock wave struck the bottom plate, seems to indicate that the optimum plenum chamber pressure may be that which balances the test section pressure ahead of the leading-edge shock.

There was no suction through the top wall, hence the shock configuration above the wedge provides a direct comparison for the perforated wall effects. The heavy lines that resemble stream lines are oil streaks resulting from the oil deposited in the air during the compression process. A filter had been ordered to eliminate this problem but delivery was delayed because of labor difficulties at the factory.

The Reynolds Number of the free stream based on the height of the test section was in the order of 1.5×10^6 for all Mach Numbers. A curve showing the variation of Reynolds Number with Mach Number for several values of supply pressure is included in Fig. 17. The two-inch tunnel normally operates at stagnation temperatures of about 100°F . A more complete description of the wind tunnel is contained in Ref. (3).

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CONCLUSION AND RECOMMENDATIONS

The few tests conducted up to the time this report was written showed clearly that shock cancellation at higher supersonic velocities is undoubtedly possible by use of perforated plates. In order to determine the optimum configurations for best results the following recommendations are made for the program of the future work:

1. Expansion of the initiated work to determine optimum perforated plate configurations to minimize shock reflection in the Mach number range from 1.8 to 3.8.
2. Continuation of the investigation of wind tunnel flow characteristics of a perforated wall with and without mass flow through the wall. The following variables should be considered.
 - a. Hole distribution in perforated plates.
 - b. Plate length and width.
 - c. Ratio of hole diameter to plate thickness.
 - d. Hole inlet configuration.
 - e. Hole coverage (blanketing)
3. Preliminary determination of shock cancellation properties of the perforated plates by use of a suitable two-dimensional model. These properties will be measured quantitatively by pressure taps and probes and qualitatively by Schlieren photographs.
4. Detailed analysis of the variables involved in defining the shock cancellation properties of perforated wind tunnel walls.

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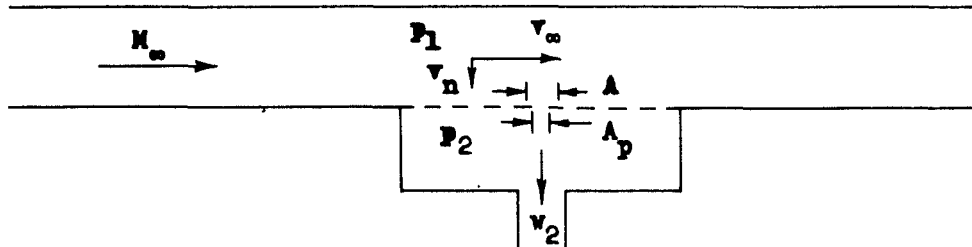
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1. Rice, Janet B., Report No. M-95630-16, United Aircraft Corporation Research Department, East Hartford, Connecticut, May, 1954, (Confidential).
2. "Power Test Codes, Supplement on Instruments and Apparatus, Part 5, Measurement of Quantity of Materials", PTC 19.5; 4-1949, published by The American Society of Mechanical Engineers, New York, New York, 1949.
3. Goldbaum, G. C., Progress Report A-1, Contract AF 33(616)-2673, Defense Research Laboratory, The University of Texas, Austin, Texas, 30 November 1954, (Confidential).

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NOMENCLATURE FOR PERFORATED WALL TESTS

Contract AF 33(616)-2673



- a = Speed of sound, feet per second.
- A = Area, square feet.
- AR = Aspect Ratio = D/t.
- D = Hole diameter, feet.
- k = Viscous loss coefficient, $\Delta p/q_\infty = k(v_n/v_1)^n$.
- k' = Viscous loss coefficient; $\Delta p/p_0 = k'(Q_p)^n$.
- m = Mass flow, slugs per second.
- M = Mach Number, v/a .
- n = Characteristic slope.
- p = Pressure, pounds per square foot.
- Δp = Static pressure differential across the perforated plate,
 $P_1 - P_2$, pounds per square foot.
- q = Dynamic pressure = $\frac{1}{2} \gamma P_\infty^2 = \frac{1}{2} \rho v^2$, pounds per square foot.
- Q = Volume rate of flow, cubic feet per minute.
- Q_p = Flow coefficient = $\frac{\rho_2 v_2 A_p}{\rho^* v^* A_p} = \frac{\text{mass flow through plate}}{\text{critical mass flow through plate}}$.
- Re = Reynolds Number, $\rho v l / \mu$.
- t = Plate thickness, feet.
- v = Velocity, feet per second.
- w = Weight flow, pounds per second.

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NOMENCLATURE (Continued)

- γ = Specific heat ratio = 1.400 for air.
- θ = Angle of characteristic slope, $n = \tan \theta$.
- λ = Ratio of open area to total area of porous plate, A_p/A .
- μ = Viscosity, pound-sec per square foot.
- ρ = Density, slugs per cubic foot.

Subscripts

- o = Stilling chamber condition.
- 1 = Free stream condition above perforated plate.
- 2 = Conditions in plenum chamber beneath perforated plate.
- ∞ = Free stream condition in wind tunnel.
- n = Normal component to plate.
- p = Defines open region of perforated plate.
- ts = Test section.
- cr = Critical.

Superscripts

- $*$ = Critical condition, $M = 1.0$.

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TABLE I

Description of Perforated Plates

P L A T E	P O R O S I T Y %	L E N G T H O F P O R O U S P O R T I O N (in.)	H O L E D I A M E T E R d (in.)	A S P E C T R A T I O $\frac{d}{t}$	A R E A P E R H O L E (in. ²)	N U M B E R O F H O L E S	O P E N A R E A (in. ²)	T O T A L A R E A (in. ²)
1	BLANK	0	0	0	0	0	0	
2a	25.6	1.953	.0595	.952	.002780	284	.78952	3.0840
2b	" "	3.906	" "	" "	" "	554	1.5401	6.0160
2c	" "	5.859	" "	" "	" "	824	2.2907	8.9480
3a	7.03	1.851	.0595	.952	.002780	83	.2307	3.2817
3b	" "	3.702	" "	" "	" "	158	.4392	6.2475
3c	" "	5.552	" "	" "	" "	260	.7228	10.2816
4a	25.6	1.946	.0995	1.592	.007775	111	.8630	3.3711
4b	" "	3.892	" "	" "	" "	213	1.6561	6.4691
4c	" "	5.839	" "	" "	" "	315	2.4491	9.5668
5a	57.188	1.953	.0995	1.592	.007775	238	1.8505	3.2358
5b	" "	3.906	" "	" "	" "	463	3.5998	6.2947
5c	" "	5.859	" "	" "	" "	688	5.3492	9.3537

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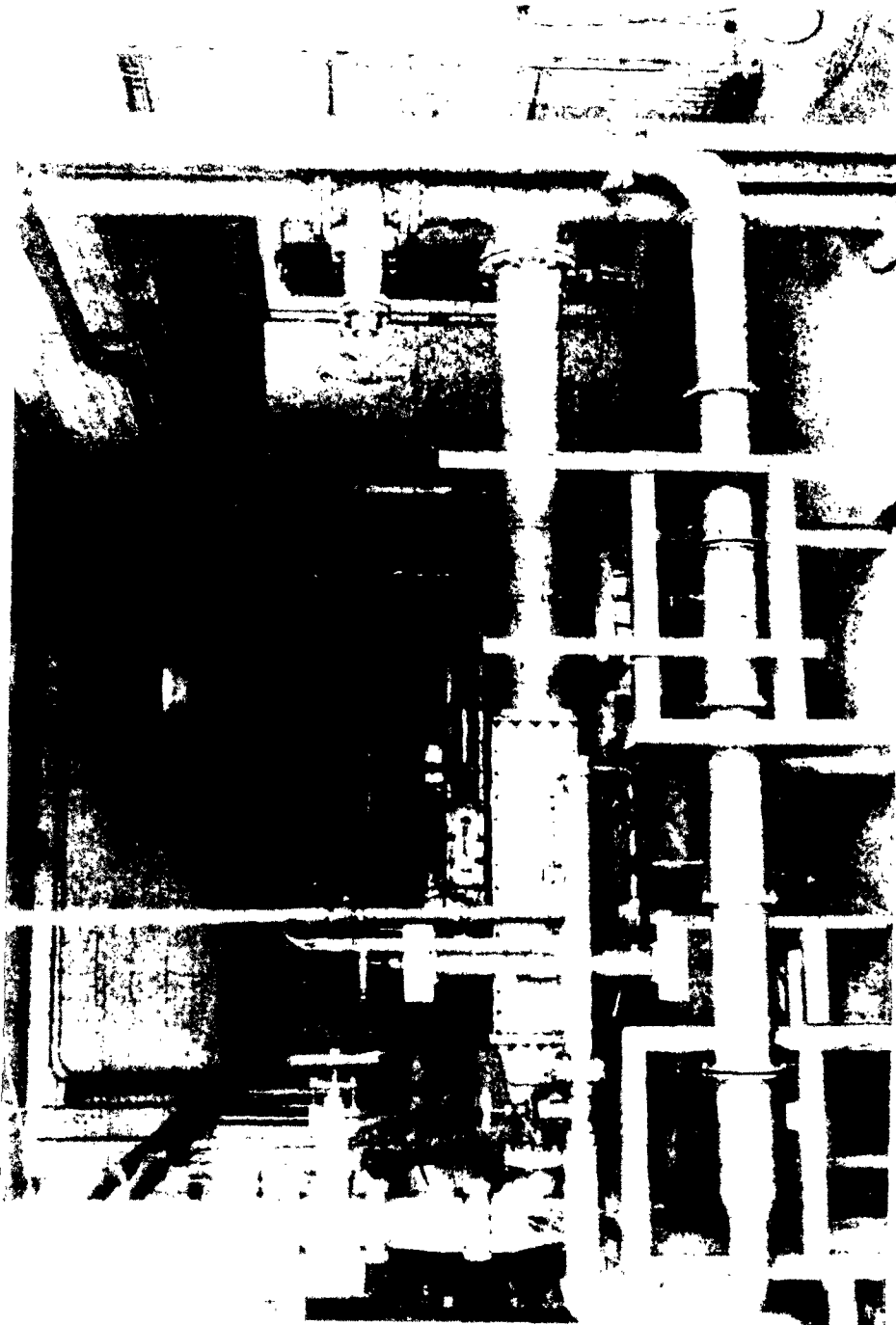


Fig. 1 - Continuous Flow Variable Mach Number Wind Tunnel Circuit

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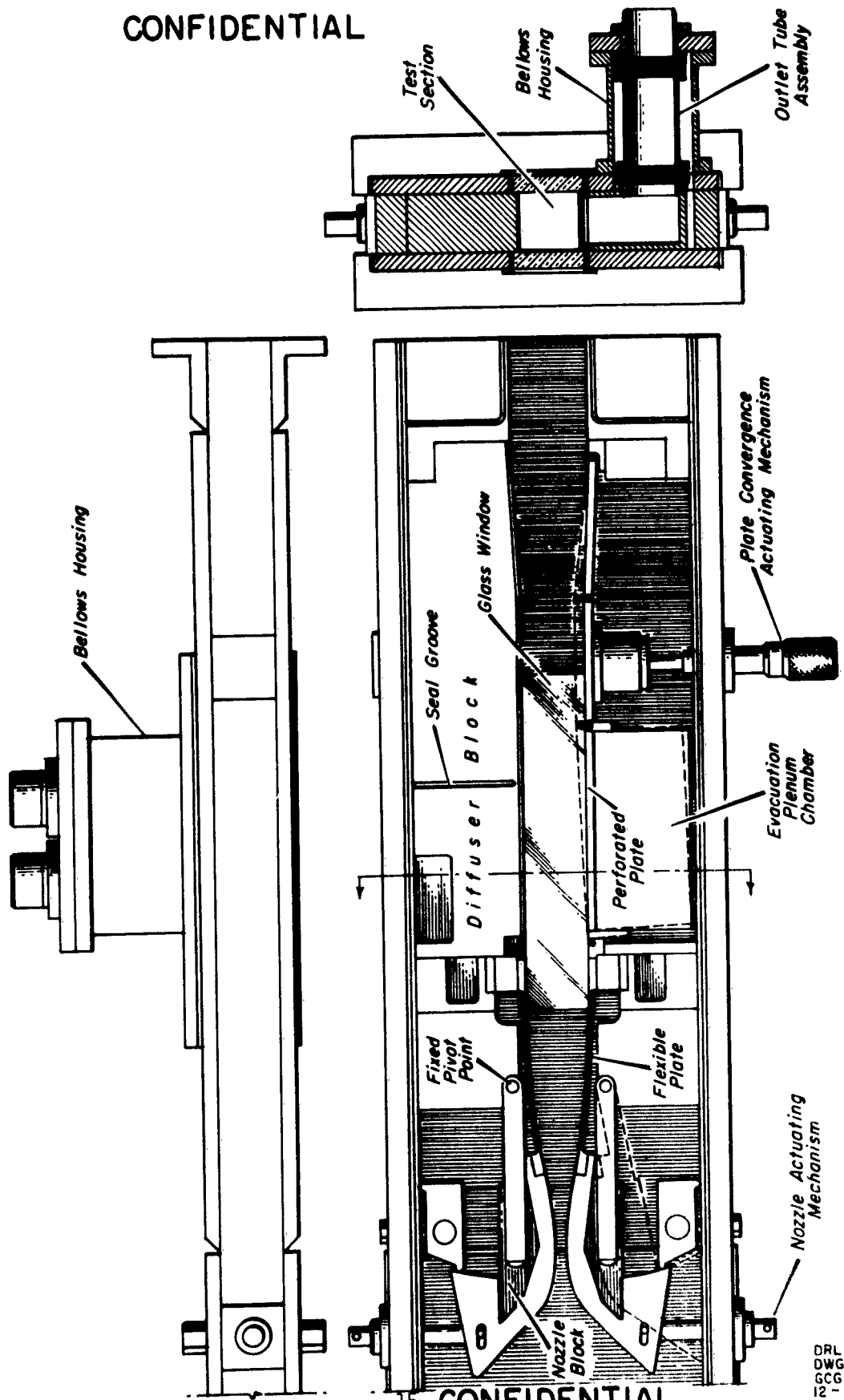


Fig. 2 - Wind Tunnel Assembly For Perforated Wall Tests
(Side Wall Removed)

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**Fig. 3 — Photograph of Wind Tunnel Assembly
For Perforated Wall Tests
(Includes Outlet Tubes and Bellows Housing)**

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Fig 4 - Wind Tunnel Assembly With Perforated Plate Installed
(Side Wall Removed)

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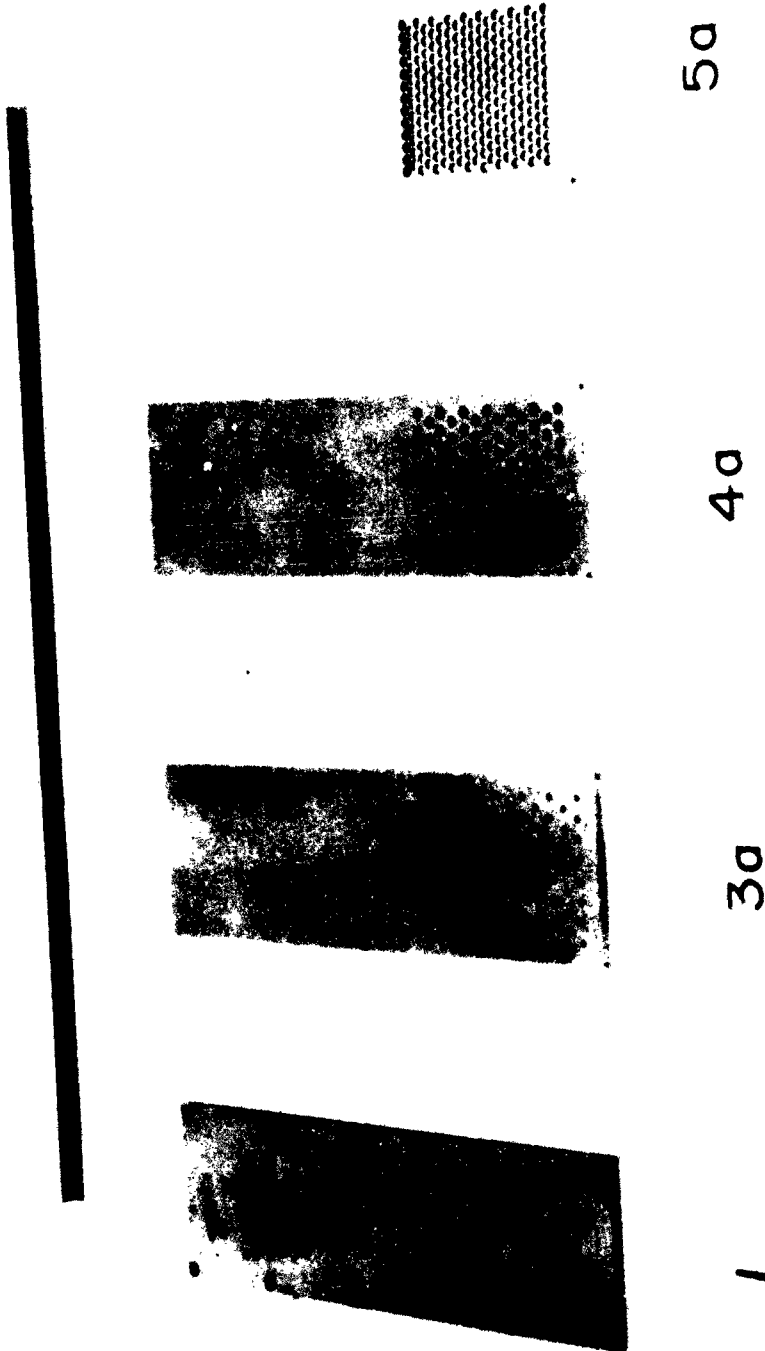


Fig. 5 - Photograph Of Perforated Plates Showing
Different Plate Porosities And Hole Sizes

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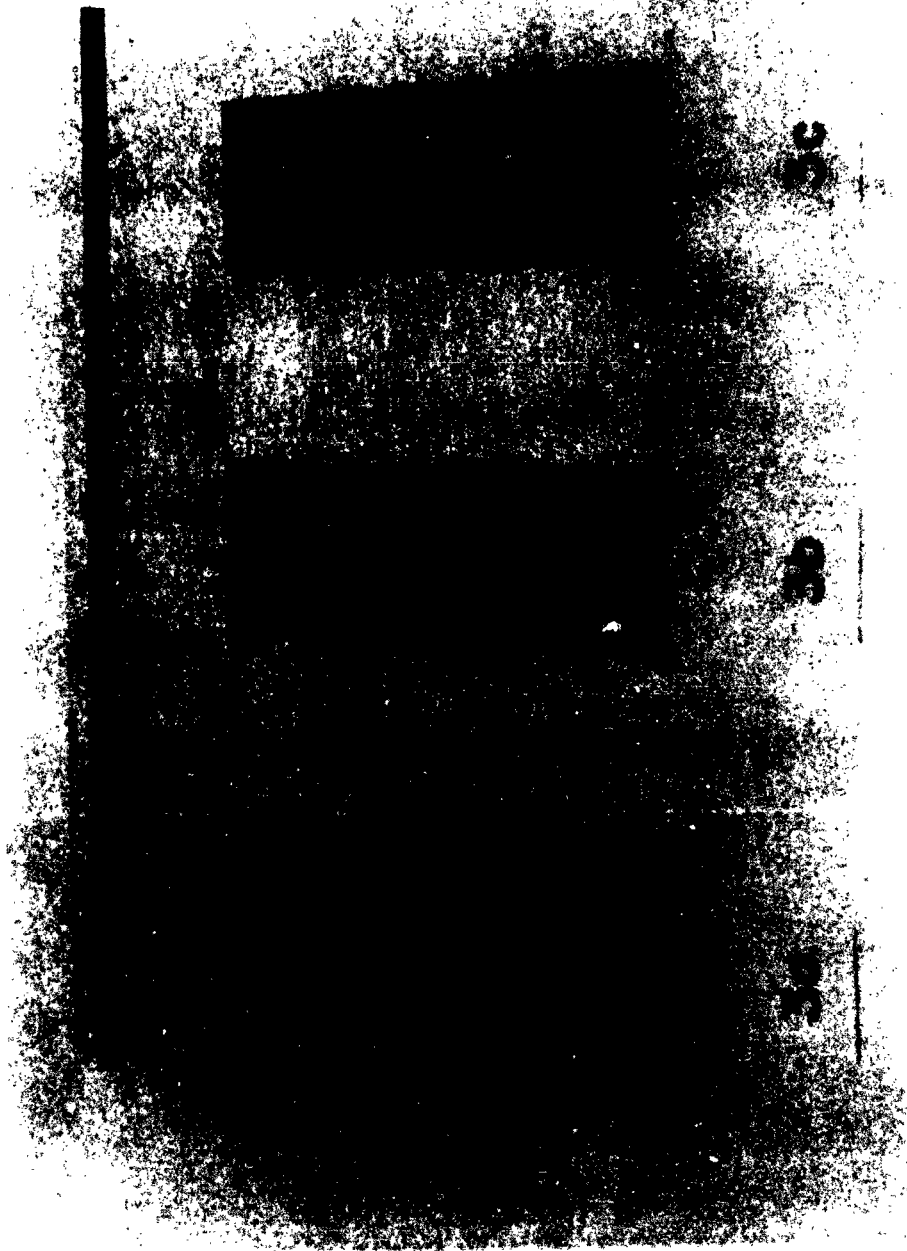


Fig. 6 - Photograph Of Perforated Plates Showing
Different Perforated Lengths

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Fig. 7 - Photograph Of Flow Measuring Nozzles

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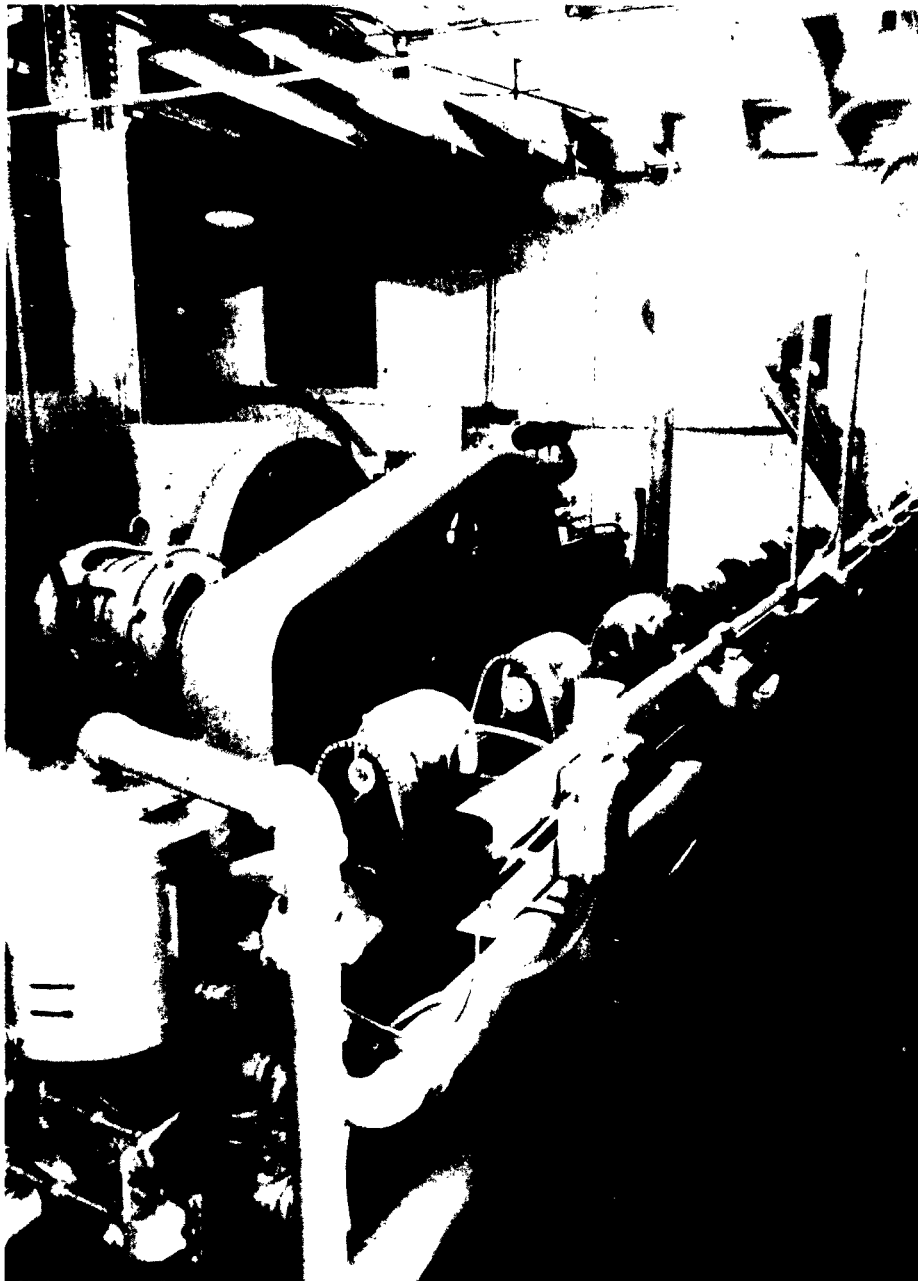
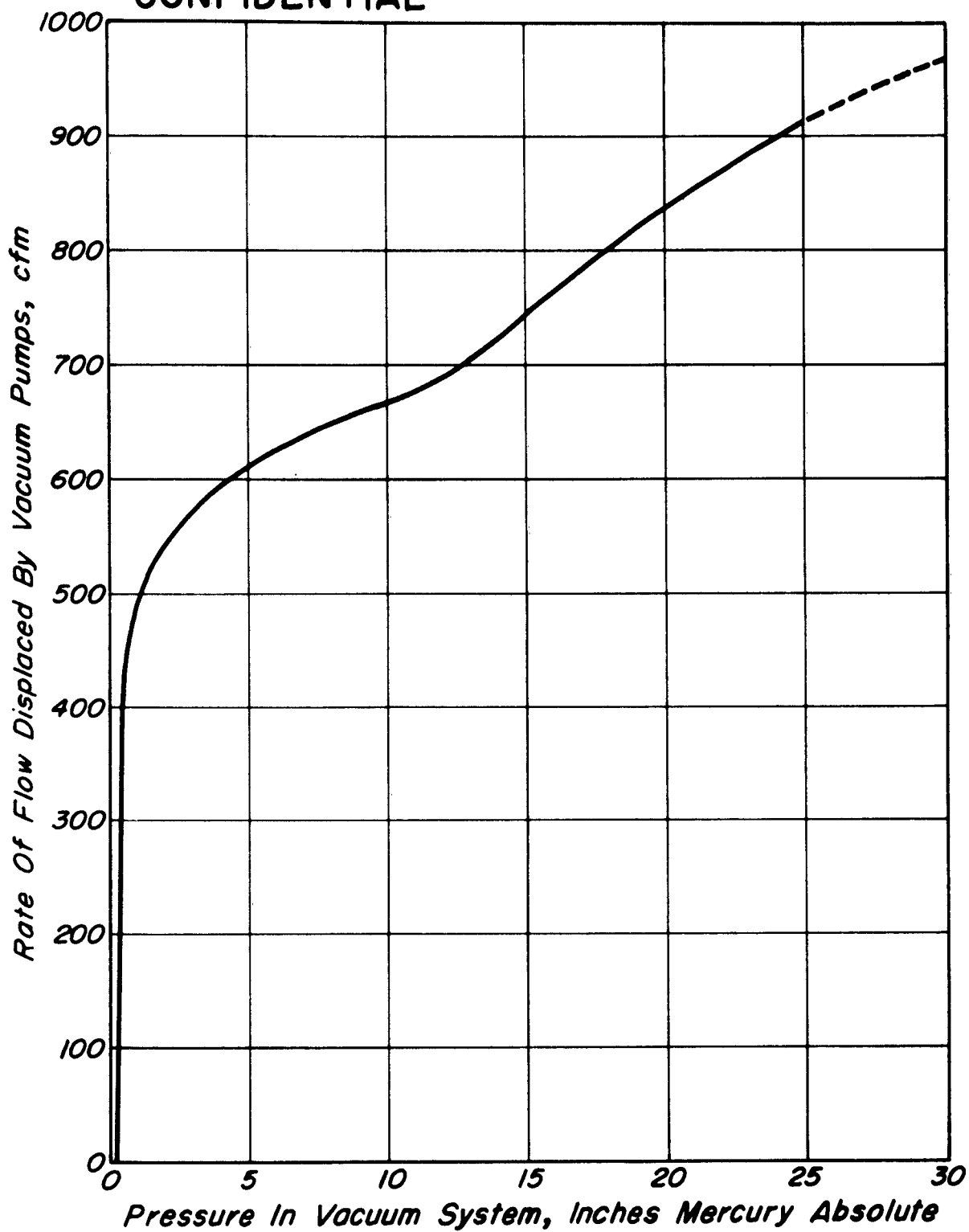


Fig. 8 - Vacuum Pump Installation

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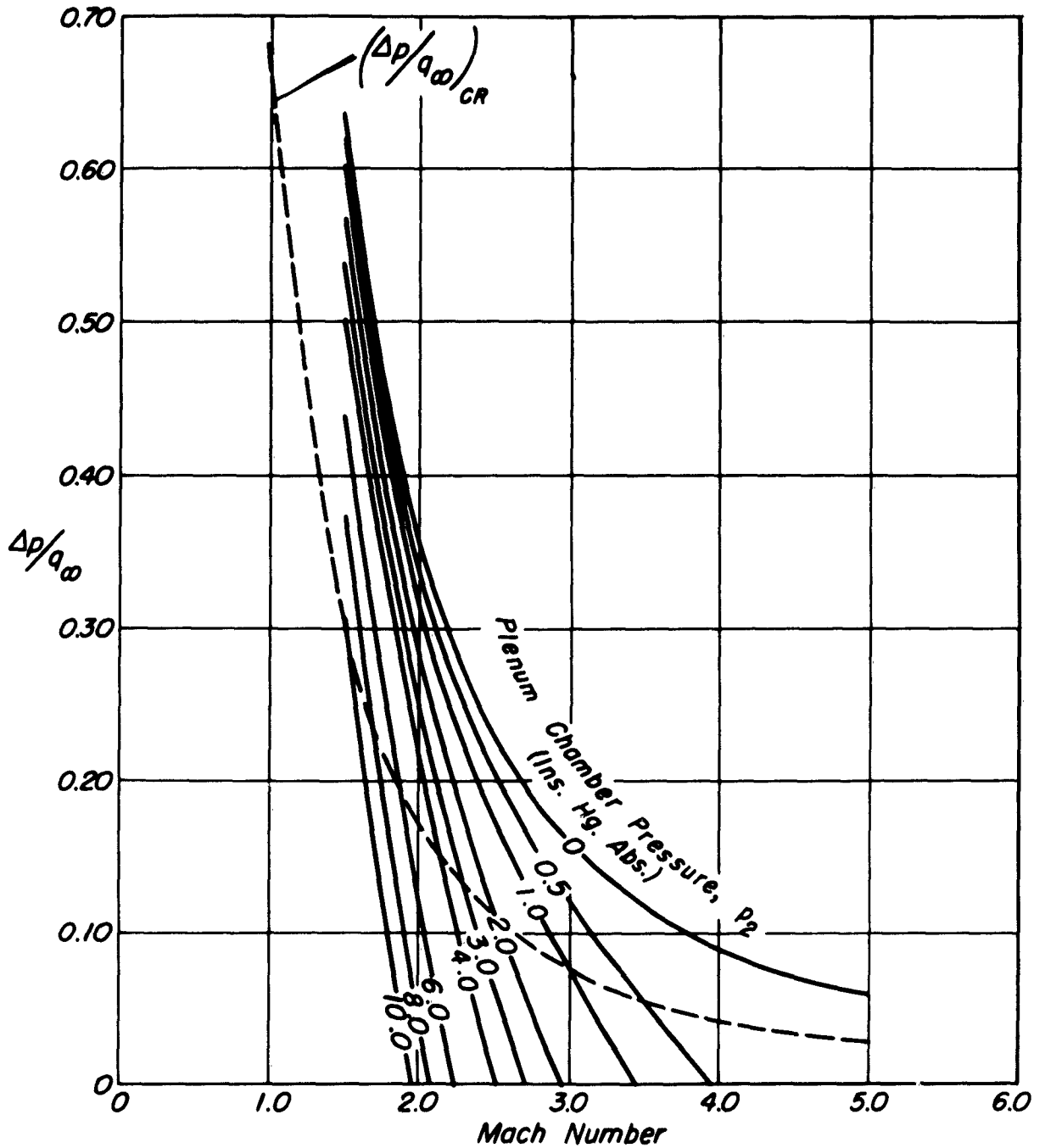


**Fig. 9 - Operational Characteristics
Of Vacuum System**

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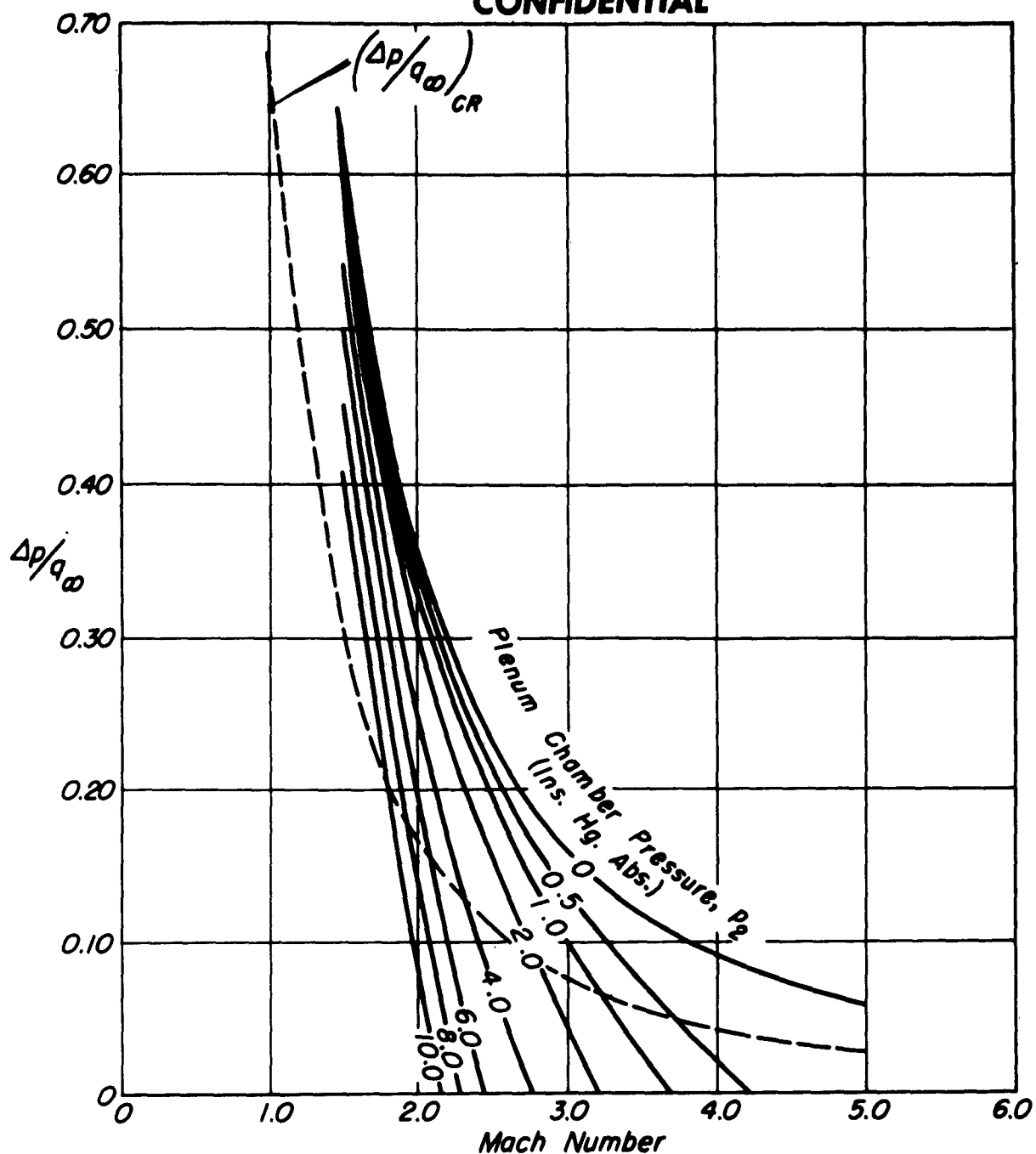


Stilling Chamber Pressure, $p_0 = 35$ psia.
Stagnation Temperature, $T_0 = 100^\circ$ F.

Fig. 10 - Variation Of $\Delta p/q_\infty$ With Mach Number
Effect Of Plenum Chamber Pressure

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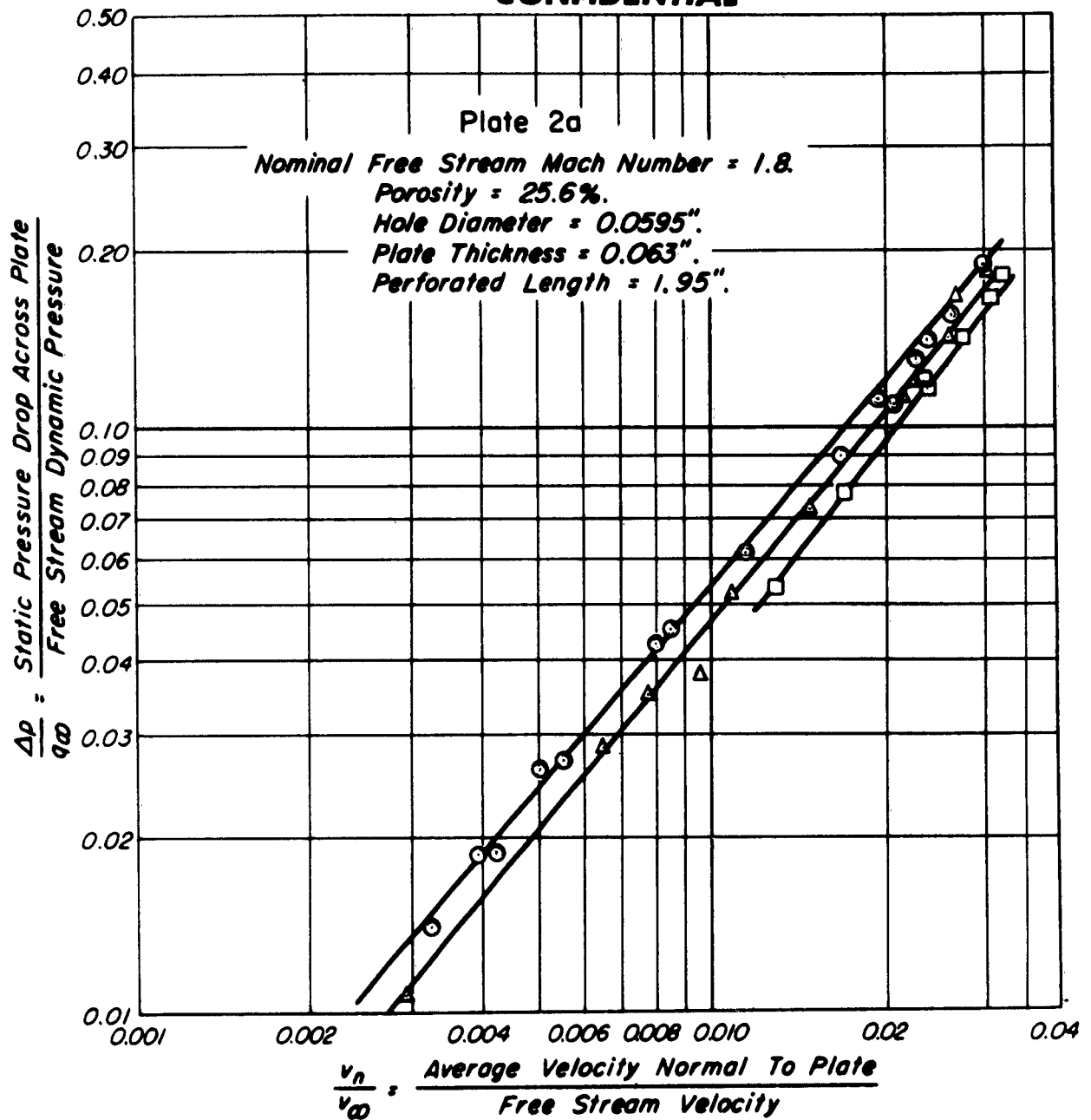
Stilling Chamber Pressure, $p_0 = 50$ psia.
 Stagnation Temperature, $T_0 = 100^\circ$ F.

Fig. 11 - Variation Of $\Delta p/q_\infty$ With Mach Number
 Effect Of Plenum Chamber Pressure

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Symbol	Plate Angle Of Attack (Degrees)
○	0
△	1.0
□	2.3

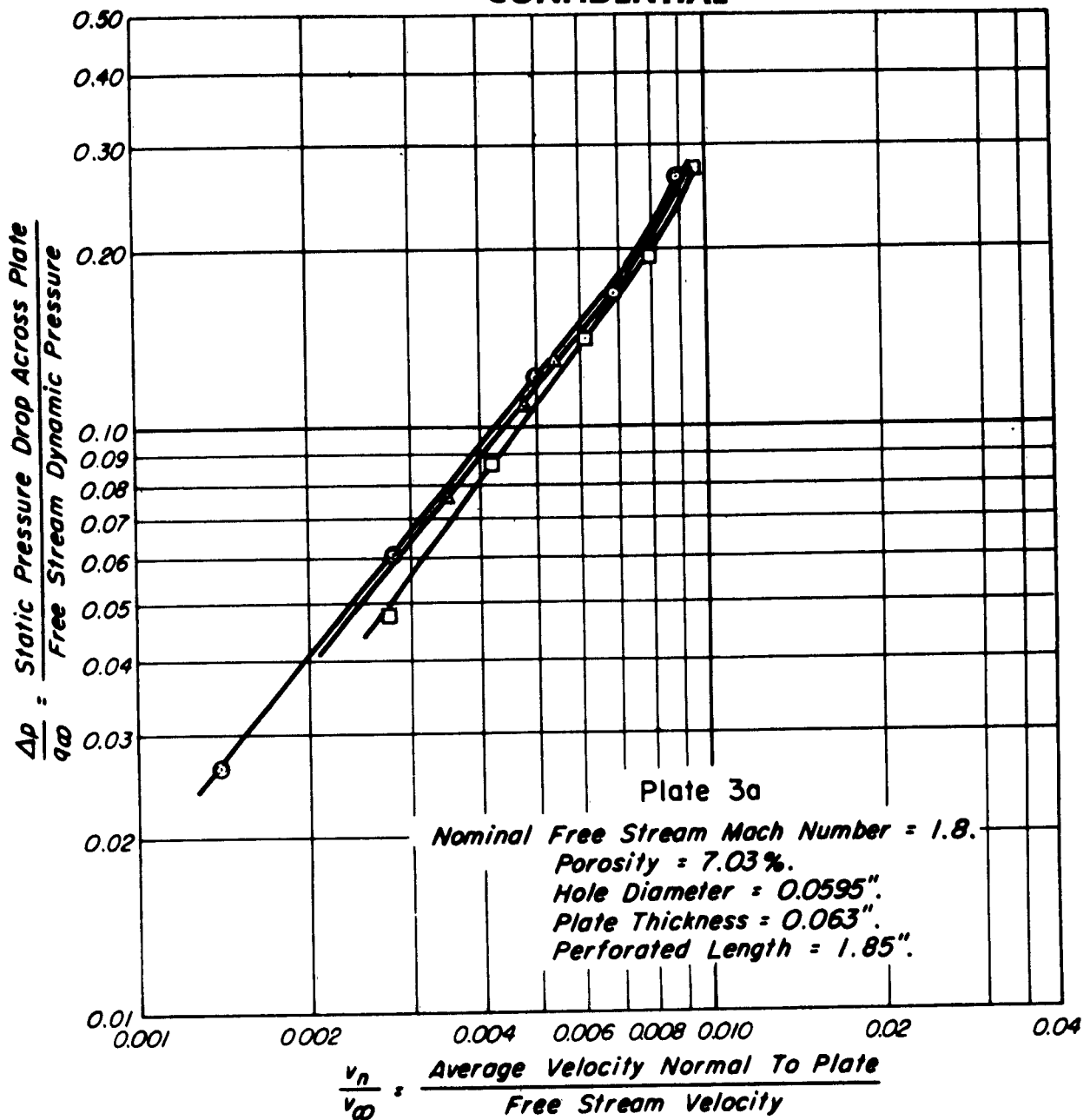
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Fig.12- Variation Of $\frac{\Delta p}{q_{\infty}}$ With $\frac{v_n}{v_{\infty}}$

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Preliminary Results.

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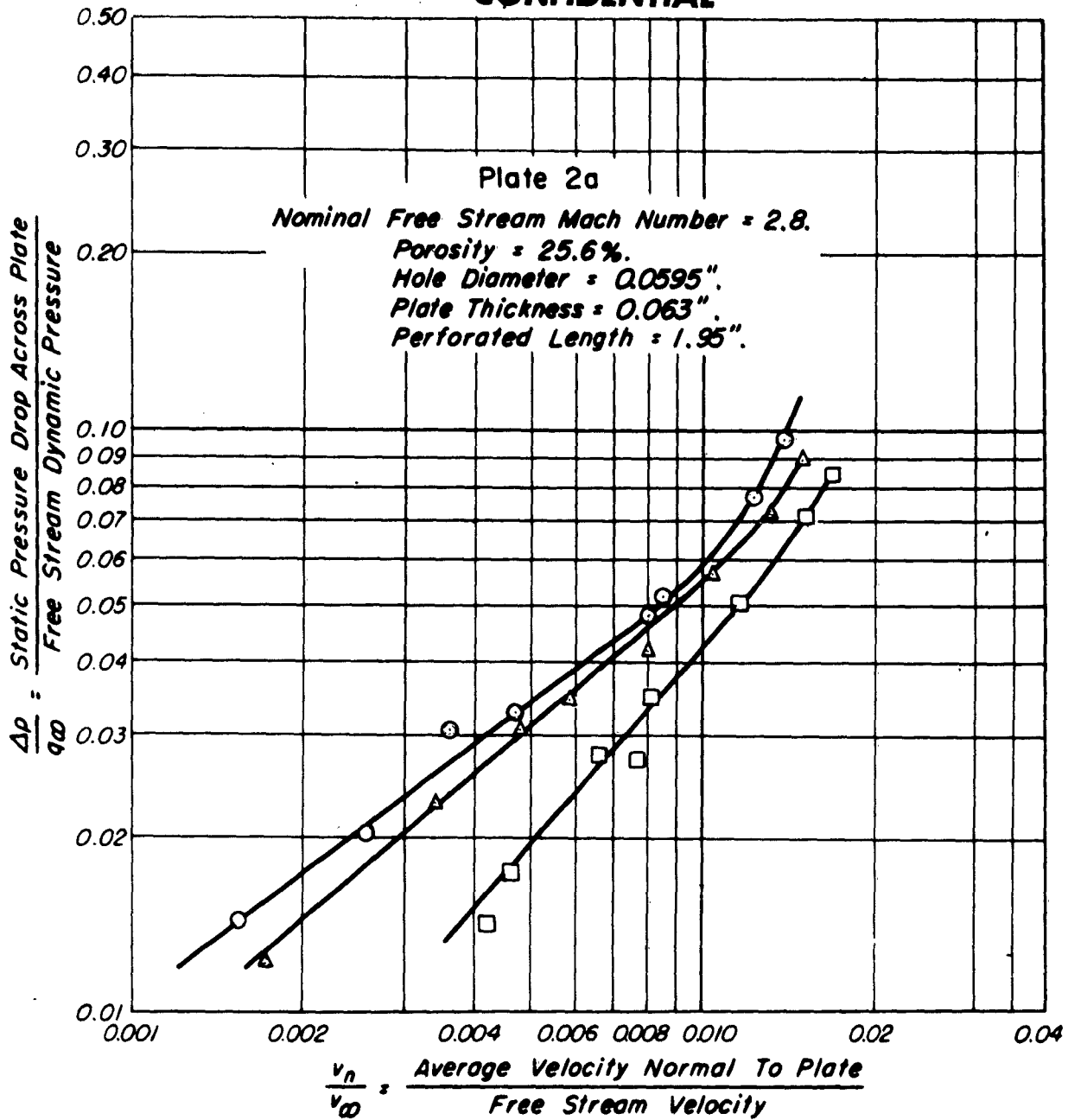


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Fig.15- Variation Of $\frac{\Delta p}{q_\infty}$ With $\frac{v_n}{v_\infty}$

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Symbol	Plate Angle Of Attack (Degrees)
○	0
△	1.0
□	2.3

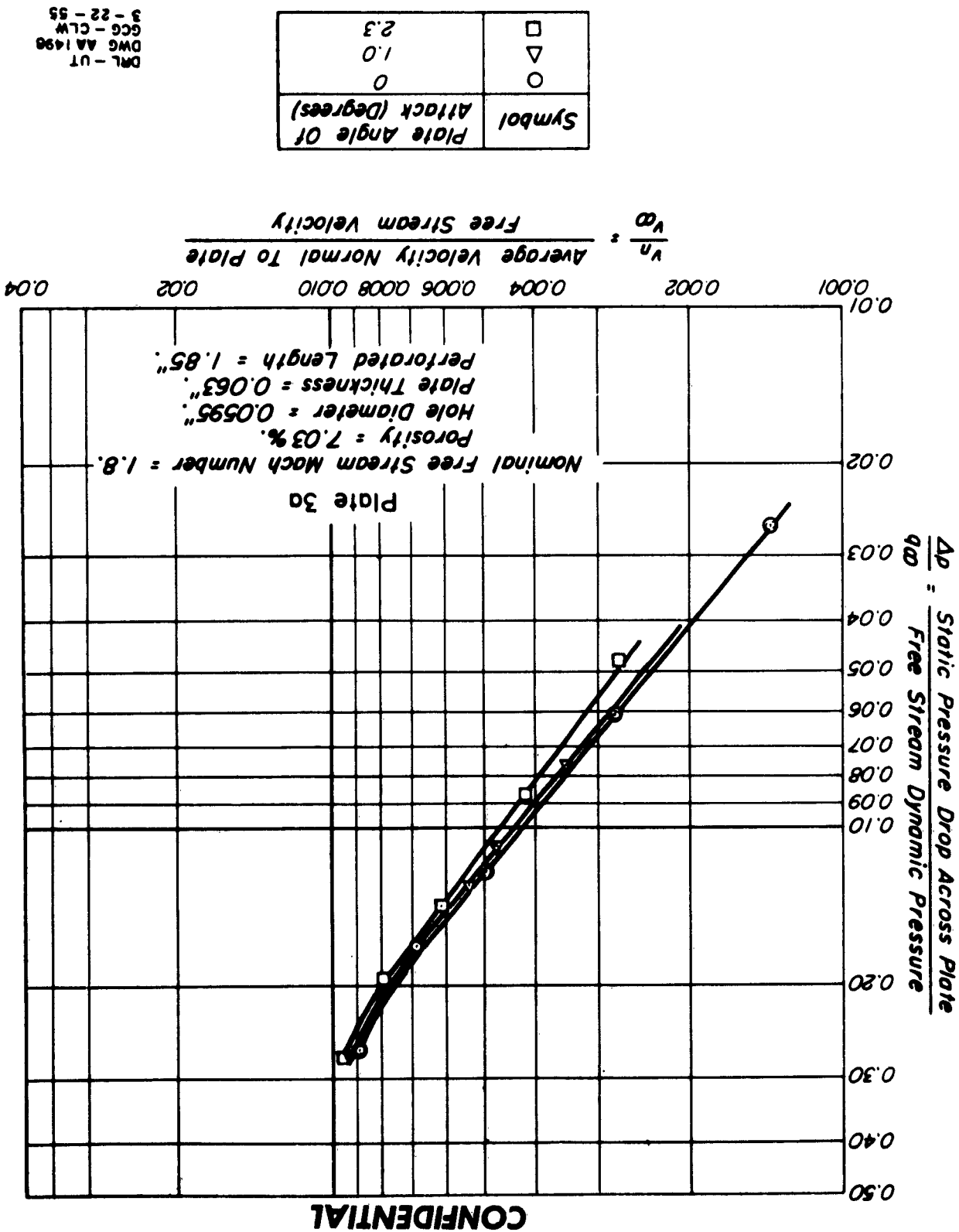
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Fig.13- Variation Of $\frac{\Delta p}{q_{\infty}}$ With $\frac{v_n}{v_{\infty}}$

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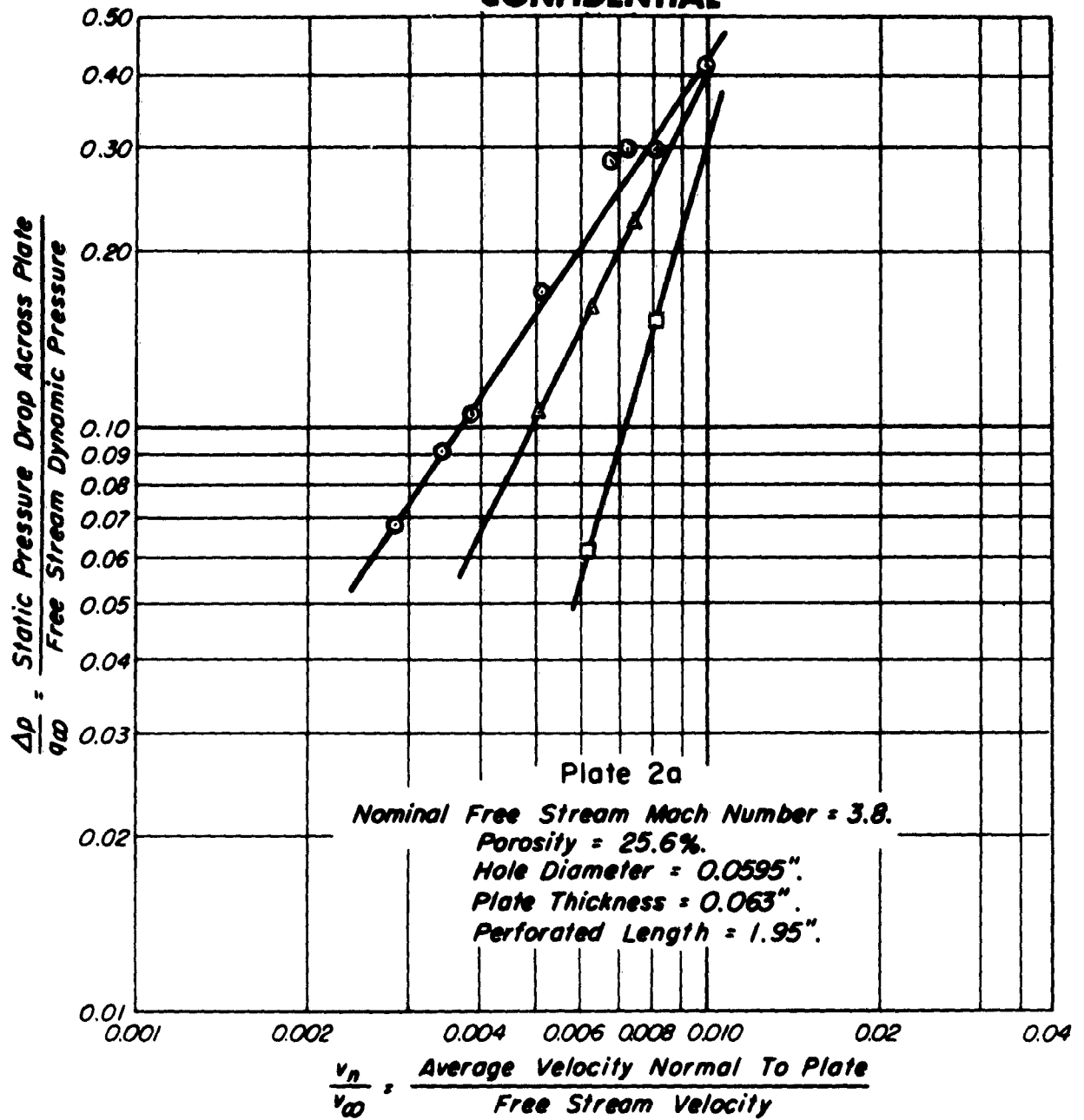
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Fig.15 - Variation Of $\frac{\Delta P}{q_\infty}$ With $\frac{V_\infty}{V_n}$



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Symbol	Plate Angle Of Attack (Degrees)
○	0
△	1.0
□	2.3

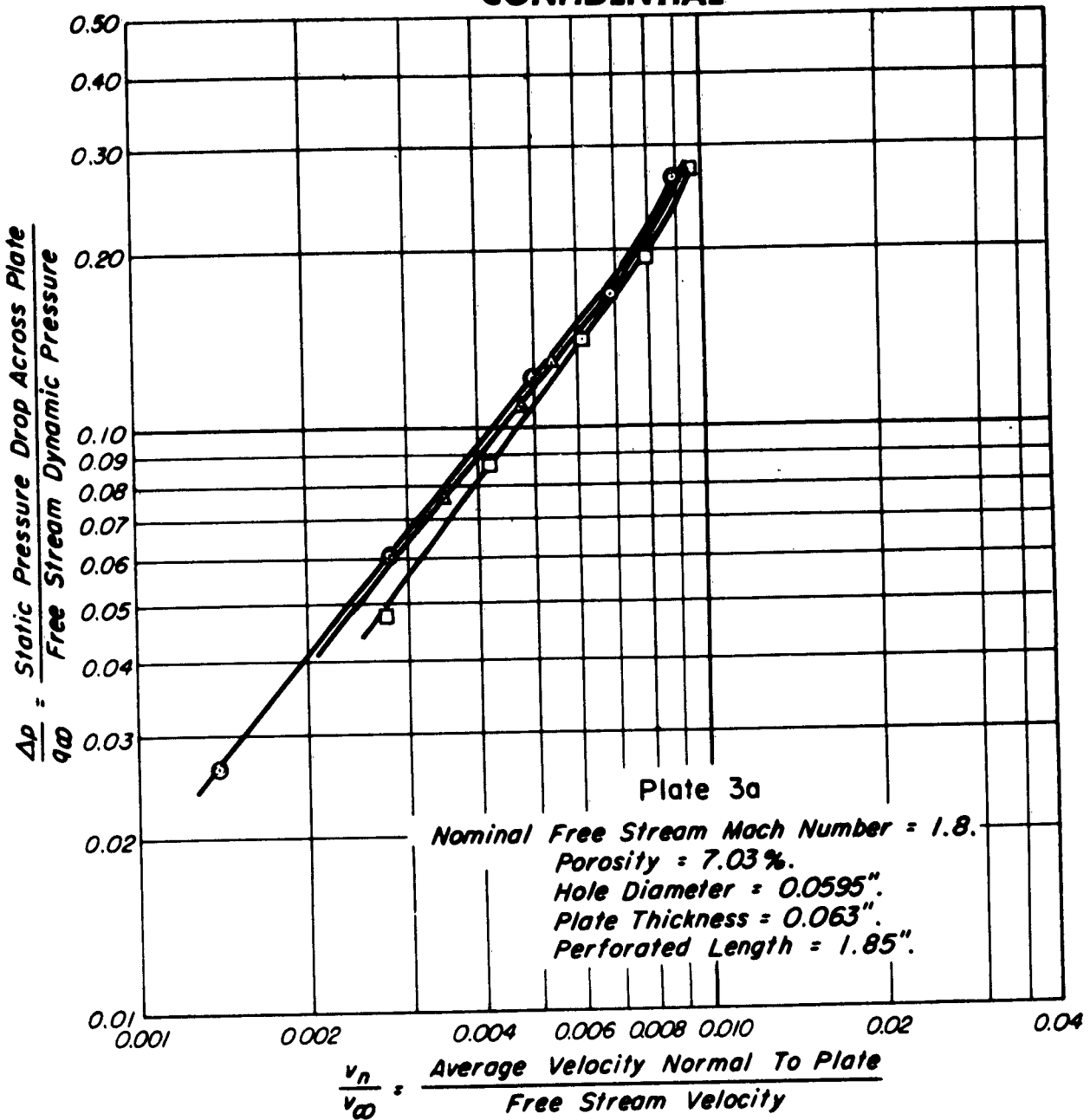
DRL - UT
 DWG AA 1497
 GCG - CLW
 3 - 22 - 55

Fig.14 - Variation Of $\frac{\Delta p}{q_\infty}$ With $\frac{v_n}{v_\infty}$

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Preliminary Results.

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DRL - UT
 DWG AA 1498
 GCG - CLW
 3 - 22 - 55

Fig.15 - Variation Of $\frac{\Delta p}{q_\infty}$ With $\frac{v_n}{v_\infty}$

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Preliminary Results.

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Fig. 16a - No Mass Flow Being Scavenged.



Fig. 16b - Maximum Mass Flow Being Scavenged.

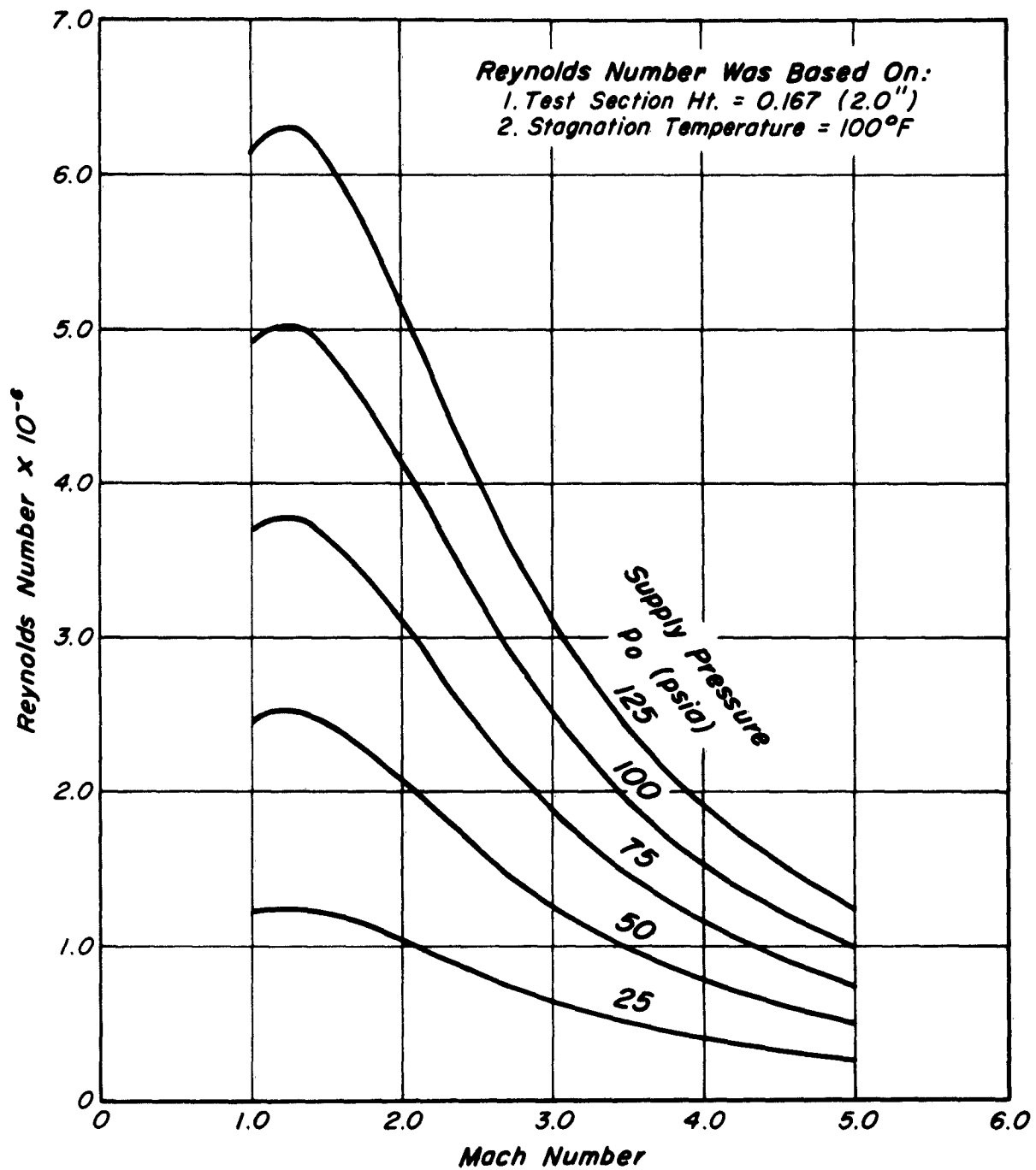


Fig. 16 - Schlieren Photographs Of Shock Wave Configurations At $M_1 = 1.8$, Ten-Degree Half-Angle Two-Dimensional Wedge

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2673 - 10

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**Fig. 17 - Variation Of Reynolds Number
With Mach Number
(Effect Of Supply Pressure)**

DRL - UT
DWG AA 1514
GCG - EJW
5 - 11 - 55

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